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Liquid biofuels in China: Current status, government policies, and future opportunities and challenges

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ABSTRACT

China, like many other countries, is promoting the development of liquid biofuel, including bioethanol and biodiesel. The Chinese government has set biofuel development targets for the coming decade and sanctioned a series of supportive policies. This paper provides a comprehensive overview of current liquid biofuel development in China, related government policies, and the potential opportunities and challenges for its future expansion. Our assessment is based on two rounds of in-depth fieldwork and a thorough literature review. The assessment shows that the prevailing concern on food security has pushed China to move from cereal-based to non-cereal-based biofuel production. Emphasis has also been put on utilizing new marginal land for feedstock production. Our assessment indicates that the targets of China's biofuel development are cautious and feasible, but on the other hand there are still severe challenges for the sustainability of such development. A better understanding of China's experience in striking a balance between energy security, food security and environmental protection would inform the debates across country boundaries and contribute to the efforts for global sustainability.

Contents

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1. Introduction

The impressive economic growth of China has naturally led to a rapid rise in energy consumption. In 2009, China produced 189 million tons of crude oil and imported another 199 million tons, which accounted for 51.3 percent of China's total oil usage in the year [1]. The rises in oil consumption and oil imports are expected to continue with the expansion of China's economy. The most recent projection of the International Energy Agency suggests that about 75 percent of China's oil consumption will be imported by 2030 [2]. The growing demand for oil imports has given rise to mounting concerns on national energy security within China. Furthermore, having become the number one emitter of greenhouse gases (GHG), China is under increasing pressure to take actions to tackle the emission issue [3].

To address the issues of both energy security and GHG emission, China has made considerable progress in renewable energy utilization, including liquid biofuels. China's renewable energy consumption totaled 250 million tons of standard coal equivalent in 2008 (excluding traditional biomass energy), accounting for about 9 percent of its total primary energy use, up from 7.5 percent in 2005. The national targets were set for a 10 percent renewables share in the overall energy mix by 2010 and a 15 percent share by 2020 [4]. In terms of liquid biofuel production, China is now the fourth largest producer in the world after the United States, Brazil, and the EU [5]. Five large-scale bio-ethanol plants were constructed between 2001 and 2007, which had a combined annual production capacity of 1.87 million tons in 2008. The actual production of these five plants in 2008 was 1.5 million tons, accounting for 79 percent of the total bio-ethanol production in China (see Table 1). The annual production targets of bio-ethanol and biodiesel set out in "The Medium and Long-Term Development Program for Renewable Energy" of 2007 are at 10 and 2 million tons respectively by 2020.

Putting the 10 million tons of bio-ethanol into perspective, although equivalent to only 14 percent of total gasoline consumption in 2009, it would lead to a demand for maize at the level of 32 million tons if the production were fully maize-based, which amounts to about 20 percent of China's maize production and 6.6 percent of China's total cereal production in 2009 [6]. Without alternative feedstock, the implication of such a bio-ethanol target on China's food security would be grave. In recognition of this dangerous implication, China's authorities have been cautious in biofuel development and have shifted emphasis from the earlier cereal-based development to non-cereal based development since 2006–2007. The Development Programming for Renewable Energy of 2007 requires that future biofuel expansion in China should be non-cereal based and new marginal land should be brought in for expanding feedstock production.

Despite the admirable policy intention, it remains highly challenging to carry out these policy goals. Given the fact that land has been the scarcest of the factor endowments in China's agriculture and Chinese peasants historically have extended farmland to an exhaustive extent, will China still have new marginal land and water resources available to support the production of feedstocks demanded by the biofuel expansion? What would be the potential impacts of liquid biofuel development on China's food security if at least part of the feedstock has to be produced on existing cultivated land? Other related questions include: What are the potential impacts of biofuel expansion on ecosystems and on the GHG emission? What are the likely trends of biofuel technology development and will the second generation biofuels (i.e., biofuels produced from celluloses) play a significant role in the foreseeable future? Although there has been an expanding body of literature addressing these questions, results from existing studies diverge and in-depth examinations and understanding have been in short supply.

This paper aims to provide a comprehensive and up-to-date overview of current liquid biofuel development in China, related government policies, and the potential opportunities and challenges for its future expansion. To gather first-hand information on China's biofuel sector and solicit opinions on the trade-off between food and biofuels from key stakeholders, we conducted two rounds of in-depth fieldwork in July 2007 and in August to October 2009. We visited all the five large-scale bio-ethanol plants, which together produced 79 percent of China's total bio-ethanol outputs in 2008. We interviewed a good mix of government officials at the central and local levels, senior managers of biofuel plants and food companies (feed, livestock producers), specialists from industry associations and research institutions. We discussed with the interviewees their assessments of the current status, prospects, problems, policies, and emerging opportunities and challenges related to the biofuel development and food-fuel trade-off. The overview and assessments presented in this paper is based on these interviews and our own thorough literature review.[1]

It is worth highlighting that the case of China is of particular academic and policy interest. In comparison with the US, Brazil, and the EU, China's pursuit of liquid biofuel development faces a much tougher constraint of food security and land availability. It is therefore a more representative picture of global biofuel development. A better understanding of China's experience in striking a balance between energy security, food security and environmental protection would update the debates across country boundaries and contribute to the sustainable development of biofuels in the developing world.

The rest of the paper is organized as follows. Section 2 examines the current status of liquid biofuel production and utilization in China. Section 3 reviews the evolution of China's biofuel policies. Section 4 analyzes the opportunities and challenges for the sustainable development of China's biofuel industry in the future. Section 5 concludes.

2. Liquid biofuel developments in China

2.1. The production of bioethanol and biobutanol

China initiated its bioethanol program ten years ago. China's bioethanol production had rapidly expanded from 30,000 tons in 2002 to approximately 1.9 million tons in 2008, making China the third largest producer of bioethanol in the world [5,7]. By the end of 2008, five large-scale bioethanol plants were under operation. Between 2001 and 2004, four bioethanol plants using stale maize and wheat were approved and established in Heilongjiang, Jilin, Anhui, and Henan provinces. However, with the running out of stale grains in 2005, all of those four plants have converted to using fresh maize as the major feedstock since then. In 2007, a cassava based bioethanol plant was approved and constructed and it commenced operation in early 2008. Table 1 shows the location, production capacity, actual production and feedstock input of the big-five bioethanol plants in 2008. The table indicates that the total maize consumed for bioethanol production by the first four plants was approximately 4.25 million tons, accounting about 2.6 percent of China's total maize production in that year. The annual output of the cassava based bio-ethanol plant was about 150,000 tons in 2008 and the plant consumed 375,000 tons of dry cassava.

In recognition of the threat posed by cereal-based biofuel production on food security, China has also been experimenting with

[1] Unless otherwise indicated, data sources in the following discussion are from these interviews.

Table 1
Location, production capacity, actual production, and feedstock use of five large-scale bioethanol plants in China in 2008.

Company name and location	Production capacity (1000 tons/year)	Actual production (1000 tons/year)	Feedstock	Feedstock input (1000 tons/year)	Market for product
Jilin Fuel Ethanol Co. Ltd, Jilin	500	450	Maize	1350	Jilin, Liaoning
COFCO[a] Bio-energy (Zhaodong) Co. Ltd, Heilongjiang	400	140	Maize	448	Heilongjiang
Tianguan Group Co. Ltd, Henan	450	440	Wheat/maize	1364	Henan, 4 cities in Hebei, and 9 cities in Hubei
Anhui BBCA Biochemical Co. Ltd, Anhui	320	320	Maize	1088	Anhui,5 cities in Jiangsu, 7 cities in Shandong, and 2 cities in Hebei
Guangxi COFCO Bio-energy Co. Ltd, Guangxi	200	150	Cassava	375[b]	Guangxi

Data source: Authors' interviews with senior managers of the "big-five" bioethanol plants in October 2009.
[a] COFCO refers to China National Cereals, Oils & Foodstuffs Import & Export Corporation, China's largest agricultural trade company.
[b] The weight of cassava is measured in dry mass using the ration of 3:1 from fresh cassava to dry cassava.

a range of non-cereal feedstock to produce bioethanol. Sweet sorghum, sweet potato, sugarcane, and cassava are the major ones being considered to use. For example, Siyi Ethanol Company in Heilongjiang Province has been using sweet sorghum for bioethanol production since 2004 on a trial basis with an annual output of about 50,000 tons. In 2007, China National Petroleum Corporation (CNPC) constructed and inaugurated a demonstration unit to produce 3000 tons ethanol per year from sweet sorghum stalks in Dongtai City of Jiangsu Province. While several demonstration-scale plants have been constructed in Sichuan, Chongqing and Shaanxi provinces to produce bio-ethanol from sweet potato, the construction of a commercial-scale bioethanol plant using sweet potato as feedstock in Hebei province, approved by National Development and Reform Commission of China (NDRC) in 2007, was temporarily suspended due to the concerns on potential competition with cereal production in the region and the logistic constraint of transporting feedstock from remote areas. Additional plants using cassava or sugarcane for bioethanol production in Guangxi and Fujian provinces are under consideration.

In terms of cellulosic based bioethanol production, although there is no commercial operation yet because of high production cost, there were eight pilot and demonstration plants in operation by December 2009, with a total capacity of 280,500 tons bioethanol per year. Of them, one built by COFCO in Heilongjiang Province uses maize stalk as the feedstock and was among the first in the world to use continuous steam explosion process, which was jointly developed by COFCO and Novozymes Denmark. Due to the relative success of some pilot projects, CNPC has teamed up with COFCO to construct 20 cellulosic ethanol plants across China, with a planned total capacity of 2 million tons [8].

The cost of bioethanol production varies across different feedstocks. As shown in Table 2, on average, the input demand for producing 1 ton bioethanol is about 3.2 ton for maize, 7.5 ton for fresh cassava, 15.3 ton for fresh stalk of sweet sorghum, 7.9 ton for fresh sweet potato, and 12.9 ton for sugarcane, respectively. In Table 2 we also present the estimated net costs of bioethanol production for different feedstocks by subtracting the value of byproducts. The estimations are based on feedstock procurement prices in 2008 and fieldwork data on the share of feedstock cost in total production cost and on the value of byproducts. The "net cost" column shows that the cassava-based production has the lowest unit cost at about 5600 yuan (US$ 824) per ton and the maize-based has the most expensive unit cost at about 6820 yuan (US$1004) per ton, with others in between. Nevertheless, it should be noted that although the cassava-based and sweet potato-based bioethanol production had a cost advantage in 2008, such advantage may be reduced if the prices of these feedstocks rise more rapidly than the prices of others following the general expansion of the bioethanol sector, as has already happened in the case of cassava. With regard to sweet sorghum stalk, unless the current liquid fermentation technique can be replaced by the newly available solid fermentation technique soon, the unavailability of the

Table 2
Production cost per ton bioethanol in 2008, by feedstock.

	Feedstock demand[a] (tons)	Price of Feedstock[b] (yuan/ton)	Costs of Feedstock[c] (yuan)	Share of feedstock cost in total cost[d] (%)	Total production cost[e] (yuan)	Value of byproducts[f] (yuan)	Net cost of bioethanol[g] (yuan)
Maize	3.2	1500	4800	60	8000	1180	6820
Cassava (fresh)	7.5	400	3000	50	6000	400	5600
Sweet sorghum (fresh stalk)	15.3	220	3366	55	6120	–	6120
Sweet potato (fresh)	7.9	410	3239	55	5889	–	5889
Sugarcane (fresh)	12.9	275	3548	55	6450	–	6450

[a] Data are from authors' interviews with technical experts in bioethanol production and review of existing publications.
[b] Data on prices of maize, sweet potato, and sugarcane are from National Agricultural Production Cost and Benefit Material 2009, and on prices of cassava and stalk of sweet sorghum are estimated by authors based on field survey.
[c] Feedstock demand times feedstock price.
[d] Shares for maize and cassava are from authors' interviews with technicians of bioethanol plants in Jilin and Anhui; shares for sweet sorghum, sweet potato, and sugarcane are based on expert estimations from various research institutes.
[e] "Cost of feedstock"/"share of feedstock cost in total cost".
[f] The major byproduct from maize-based bioethanol production is DDGS (Dried Distillers Grains with Solubles). Major byproduct from cassava-based bioethanol is the fiber residuals of cassava, which is used for power generation. The value of CO_2 is not included here because CO_2 has not been collected for commercial use in China's bioethanol plants. Because bioethanol plants which use sweet sorghum, sweet potato, or sugarcane are not in commercial operation, values of byproducts from these plants are not available.
[g] "Total production cost" minus "value of byproducts".

stalk in the off-harvest seasons implies that the maximum operational period of the plants is about 3–4 months a year, leading to much higher real annual economic cost than that suggested by our unit-cost accounting as presented in Table 2.

China has also paid attention to the development of biobutanol production. Biobutanol is easier to blend into gasoline than bioethanol because its length of hydrocarbon chain is more similar to gasoline than ethanol. In addition, it has a higher octane rating and is less corrosive than ethanol. The North China Pharmaceutical Group Corporation (NCPC) has kept a production unit with a capacity of 12,000 tons per year which can be dated back to the 1980s. It is expected that the annual capacity of this unit will be expanded soon to 15,000 tons per year by means of technical improvements. The biobutanol plant of Jiangsu Lianhai Biological Technology Co., Ltd, in Haimen City in Jiangsu Province, is regarded as the world's largest biobutanol plant. It uses cassava starch as feedstock. Its first production unit, constructed between October 2007 and September 2008, is in effective operation and has an annual output capacity of 50,000 tons of biobutanol and acetone. The second unit was brought into production in early 2010 and the third unit is expected to become operational in June 2011. The total designed capacity of biobutanol production is 200,000 tons per year [9]. R&D efforts on producing biobutanol from non-food crops have been active as well and recently a plan to build a demonstration plant with a capacity of 100,000 tons biobutanol produced from non-food crops has been approved [8].

2.2. Production of biodiesel

Since 2001 China has developed a large and growing biodiesel producing capacity. By early 2009, China had a total of some 2.1 million tons of biodiesel producing capacity. However, in comparison with ethanol, the biodiesel projects are smaller in size, more dispersed, and have had much lower utilization rates due to shortage and instability of feedstock supply. For example, the 2008 total biodiesel production is estimated at the level of 0.31 million tons only, with a capacity utilization rate well below 20 percent. Unlike their US or EU counterparts, who mainly use fresh vegetable oil or soybeans as feedstock, China's plants have had to rely on the salad oil waste, used oils, waste animal fats, and wild oilseed plants to produce biodiesel [10]. With the first-generation technology, biodiesel production needs a stable supply of lipid or vegetable oil as feedstock, but there is a persistent shortage of these oils in China. China is a net importer in all the major edible vegetable oils and imported more than 8 million tons of vegetable oil each year in 2008 and 2009, being the largest importer in the world. China is also the largest importer of soybean in the world, with a scale of 37.4, 42.6 and 54.8 million tons in 2008, 2009 and 2010, respectively [6,11]. The imported soybean is mainly used for producing edible vegetable oil and animal feed. China is still far away from a position being able to rely on imported vegetable oil and soybean for biodiesel production.

Given the shortage of crop-based feedstock supply, China has been looking to develop biodiesel based on seeds of energy trees, such as *Jatropha*, *Xanthoceras sorbifolia*, and *Pistacia chinensis*. Among various species of energy trees, *Jatropha* is often considered as one of the most favorable feedstock trees in China, and is now the focus of the country's biodiesel program. The State Forestry Administration (SFA) records show that *Jatropha* area reached 15 million ha in 2008. However, total seed output is still at a very low level because most of the *Jatropha* tree was planted after 2005.[2] *Jatropha* is mainly planted in subtropical areas of China including Yunnan, Sichuan, and Guizhou provinces. With active participations by the government and oil companies, *Jatropha*-based biodiesel industry has started to boom in these provinces since 2006. According to the targets of these three provinces on biodiesel production, it is expected to have about 167 million ha of *Jatropha* plantation on hilly and marginal lands in next 10–15 years in those provinces. However, enthusiasm in pursuing *Jatropha*-based biodiesel development was seriously undermined by the sharp (but temporary) decline of oil price in 2008. The big-three oil companies of China,[3] who have planned large investments in *Jatropha* plantation, have slowed down or temporarily shelved their biodiesel program.

2.3. Marketing system of liquid biofuels

To ensure the consumption market for bioethanol, China started in 2002 to promote a mixture of gasoline (90%) and ethanol (10%), i.e., E10, for automobile fuel on a pilot basis in five cities, three in Henan Province (Zhengzhou, Luoyang and Nanyang) and two in Heilongjiang Province (Harbin and Zhaodong). This pilot scheme was extended in 2004 to five provinces (Heilongjiang, Jilin, Liaoning, Henan and Anhui) and 27 cities in Hebei, Shandong, Jiangsu and Hubei (cf. the last column of Table 1). In 2008, Guangxi Province joined the experiment following the commercial operation of its cassava-based bioethanol plant. The gas stations in the 2004 pilot areas were required to switch fully to E10 by the end of 2005.

In China, the refining and retailing of automobile fuels are controlled by the big three state-owned oil companies, CNPC, Sinopec, and CNOOC. As a consequence, all bioethanol for blending must be sold to those three companies and be blended with gasoline in their facilities before the final selling. Taking the example of Jilin Fuel Ethanol Co. Ltd, the largest bioethanol producer in China, all of its bioethanol output is shipped to nearby blenders of CNPC by rail. These blenders are in charge of all the remaining businesses including storage, blending, and delivery of E10 to the retail outlets. CNPC has about 20 ethanol blending stations in Jilin Province.

Unlike bioethanol, biodiesel has not been promoted by the government as a transport fuel. At present there are no specific policies or schemes parallel to the bioethanol ones for the promotion of using biodiesel as a transport fuel. In fact, biodiesel has been mainly used as fuel in local factories or construction machineries. As a consequence, the biodiesel industry in China is largely unregulated and biodiesel plants do not need to be licensed by the central government. Because biodiesel plants tend to be much smaller than bioethanol plants and do not require the same degree of regulatory oversight, there is significant involvement from the private sector in a more or less free-market environment [13]. On the other hand, attracted by the great potential of *Jatropha*-based production, the big-three state-owned petroleum companies are starting to invest in proposed biodiesel plants and will join the market in the foreseeable future.

3. Legislations and policies on liquid biofuel development

3.1. Promotion of bioethanol development

Technological preparation for commercial production and utilization of liquid biofuel had been on the way before 2001. Research and development efforts for the use of biofuel in transportation sector were carried out mainly under the support of the Ministry

[2] Although *Jatropha* trees can produce seeds in the first year of their plantation, the most likely global average yield per hectare is 0.5, 1.5, 3.0, 5.0, and 6.5 ton/ha in year 1, 2, 3, 4 and 5, respectively. The full recovery of the investment in plantation needs 5 or more years [12].

[3] They are China National Petroleum Corporation (CNPC), China Petrochemical & Chemical Corporation (Sinopec), and China National Offshore Oil Corporation (CNOOC).

Table 3
Major legislations and policies regarding China's liquid biofuel development.

Year	Policy documents	Main points of the policies
Pre-2000	No specific government policy	Since 1980s, China has been supporting liquid biofuel development through investment in R&D and biofuel technologies.
2001	Special Development Plan for Denatured Fuel Ethanol; Bioethanol Gasoline for Automobiles in the 10th Five-Year	To experiment with bioethanol production using the stale grain stocks using supportive measures.
2002	Pilot Testing Program of Bioethanol Gasoline for Automobiles; Detail Regulations for Implementing the Pilot Testing Program of Bioethanol Gasoline for Automobiles	National standards for denatured bioethanol and E10 were formulated; 5 cities in Henan and Heilongjiang selected to use E10.
2004	Expanded Pilot Testing Program of Bioethanol Gasoline for Automobiles; Detail Regulations for Implementing Expanded Pilot Testing Program of Bioethanol Gasoline for Automobiles	Five provinces and 27 cities in another four provinces were selected to participate in the second phase of expanded testing.
2004	Guidance of Ministry of Finance on covering the loss of bioethanol plants from bioethanol productions	To cover the loss of plants from bioethanol production, direct subsidy to bioethanol production was set up for 2004–2008.
2005	Renewable Energy Law of China	Promote the development and utilization of renewable energies, including liquid biofuels.
2005	Supportive policies of Ministry of Finance on bioethanol production	A set of supportive policies for bioethanol production and extension was released.
2006	Announcement regarding strengthening management of bioethanol projects and promoting healthy development of ethanol industry,	Restrict market access of bioethanol production; encourage the development of non-cereal based bioethanol.
2006	Policy provision on financial support to biofuel and biochemical industries	Financial supporting policies on biofuel production were adjusted.
2006	Guidance on the Implementation of financial support to non-cereal based biofuel development	Central government will subsidize the construction of non-cereal based biofuel plants through low interest low and direct subsidy
2007	Medium and Long-term Development Plan for Renewable Energy	Set the targets of biofuel production in 2010 and 2020
2007	Development Plan of China's Agricultural Bioenergy Industry	Major feedstocks may be used for liquid biofuel development was listed
2007	Temporary policy provision on financial subsidies to production bases of feedstocks for biofuel and biochemical industry	Bioenergy trees and non-cereal feedstocks planted on marginal lands will be subsidized by 3000 yuan/ha, and 2700 yuan/ha, respectively.
2007	Planning for China's Bio-forestry development	A target for energy tree plantation by 2020 was set.

Data source: authors' compilation based on various government documents on policies, regulations, and laws.

of Science and Technology [14]. At that stage, financial supports were granted to the development of processing technologies of bioethanol, biodiesels and fermented methane gas. A number of laboratory trials were carried out under the "National High Technology Research and Development Initiative" (known as "863 Plan"). After years of government supported research, the technology for maize-based commercial production of bioethanol was more or less in place by 2000.

3.2. The stage of pilot use of biethanol

From 2001 to 2005, Chinese government sanctioned a series of policies and legislations to promote production of bioethanol and pilot distribution of the blended E10 automobile fuel (cf. Table 3). In early 2001, the First Five-Year Plan for Bioethanol and the Special Development Plan for Denatured Fuel Ethanol and Bioethanol Gasoline for Automobiles in the 10th Five-Year Plan (2001–2005) were announced. The main goal of the Plan was to experiment with bioethanol production, marketing, and support measures [15]. The plan considers stale maize and wheat from the state grain stocks as the major feedstocks. To facilitate the implementation of the plan, a national leading group was set up. The group was lead by NDRC and the top two state-owned oil companies, CNPC and Sinopec, with participation of other 8 ministries.

In early 2002, two detailed implementation guidelines, the Pilot Testing Program of Bioethanol Gasoline for Automobiles and Detail Regulations for Implementing the Pilot Testing Program of Bioethanol Gasoline for Automobiles, were jointly issued by NDRC and seven other relevant ministries. National standards for denatured fuel ethanol and E10 for automobiles were formulated and implemented. Four bioethanol production plants were approved for establishment. The marketing of E10 for the automobile sector was initiated in Zhengzhou, Nanyang, and Luoyang of Henan Province and in Harbin and Zhaodong of Heilongjiang Province.

With the experience gained from the first phase of testing, Chinese government decided to extend the pilot program in 2004. Two guidelines on the extended pilot program were issued in early 2004, including the Extended Pilot Testing Program of Bioethanol Gasoline for Automobiles and the Detail Regulations for Implementing the Extended Pilot Testing Program of Bioethanol Gasoline for Automobiles. The new policies sanctioned the expansion of E10 use in five provinces and 27 cities of another four provinces (cf. Section 2.3). The policy provision to cover the losses incurred in bioethanol production was announced in the same year by Ministry of Finance (MOF). According to this provision, the expected subsidies per ton of bioethanol production would be at RMB 2736, 2395, 2054, 1373, and 1373 yuan in each year from 2004 to 2008, respectively.

The Renewable Energy Law of China was passed in the National People's Congress in March 2005 and came into effect on 1 January 2006. The law sets out definitions of biofuels and confirms China's commitment to encouraging the use of biomass fuels. It establishes a Renewable Energy Fund specifically to assist with biofuel technology research and development, standards development and demonstration projects and to support biofuel investigation, assessment of raw materials resources, information dissemination and domestic related equipment manufacturing. Under the guidelines of the Renewable Energy Law, the MOF formulated in 2005 the new supportive policy provisions as follows. First, the 5% consumption tax on all bioethanol under the E10 program was waived. Second, the value-added tax (normally 17%) on bioethanol production was refunded at the end of each year. Third, a fixed level of direct subsidy was offered by the central government to ensure a motivating profit for each bioethanol plant. That is, if any of the big-four bioethanol plants were to record a loss in bioethanol production and marketing, it would receive a subsidy sufficient to cover the loss and to grant a reasonable profit. Also under the guidelines of the Renewable Energy Law, the government guaranteed a market for the bioethanol produced of the big-four state-owned plants. Nevertheless, private plants are not allowed to enter the E10 market.

3.2.1. Shift away from cereal-based bioethanol production

The initial motivation for establishing the bioethanol industry was primarily in response to excessive grain reserve stocks in the

leading grain production provinces. For example, storehouses in Jilin Province in 2001 bulged with maize stocks after several years of good harvests, leading maize prices to plunge to 10-year lows. The nominal stockpile of cereal in Henan Province totaled 35 million tons, reflecting an annual surplus of maize and wheat of 4–5 million tons [16]. The cereal-based bioethanol production was originally intended to utilize old cereals (2 years old or more) from government stocks. However, in real production process both new and old cereals have been used. The rapid expansion of maize- and wheat-based bioethanol production quickly showed the potential trend to reduce cropland available for food grain production. This competition in combination with the sharp increase of food price on international market in 2006 and 2007 led to increasing concerns on food security among researchers and policymakers. As a consequence, Chinese government started to reassess and adjust its bioethanol development strategy.

In 2006, NDRC issued a policy announcement reaffirming that any new bioethanol plant must be approved by the Central Government before construction [17]. To encourage the development of non-cereal based bioethanol, this policy announcement also makes it clear that any new bioethanol production based on cereal crops will not be supported and subsidized. In December 2006, MOF also adjusted its financial support policy [18]. The “fixed level” of direct subsidy to bioethanol plants postulated in the 2005 policy was replaced by “flexible subsidy for loss”. It means that while the 2005 policy ensured a fixed level of profit for each bioethanol plant, the new policy only ensures a reasonable level of profit for the whole bioethanol industry. This implies that the subsidy level will be same for each unit of output and thus those plants with lower production costs would gain a higher level of profit while those with higher production costs might make losses. To encourage the production of non-cereal based bioethanol, the MOF also announced that it will provide financial support to non-cereal bioethanol plants in the form of low interest loans and direct subsidies [19]. To promote the production of feedstocks on marginal lands, the MOF in 2007 further stated that firms reclaiming new marginal lands for non-cereal feedstock production will get a one-off subsidy of RMB 2700 yuan per hectare [20].

On 31st August 2007, the NDRC issued the Middle and Long Term Development Plan for China’s Renewable Energy. The plan clearly stated that “biofuel must not compete with grain over land, it must not compete with the food that consumers demand, it must not compete with feed for livestock, and it must not inflict harm on the environment.” The targets for annual bioethanol production were scaled down from the original ambitious figure of 6 million tons by 2010 and 15 million tons by 2020 to a more realistic one of 4 million tons by 2010 and 10 million tons by 2020 [21]. Under the guidelines of this national plan, the Ministry of Agriculture (MOA) also laid down the Development Plan of China’s Agricultural Bioenergy Industry (2007–2015). In the same year, the first cassava-based plant for bioethanol production, Guangxi COFCO Bioethanol Company, was approved by the NDRC.

3.3. Policies on biodiesel development

In comparison with the bioetnanol sector, policy provisions in the biodiesel sector have lagged behind and been less developed. There has been no policy scheme analogous to the bioethanol pilot program to promote biodiesel development. Policies which provide non-nominal supports to biodiesel development only came out after 2005. In fact, the policy issued by MOF in 2006, Financial Supportive Policies to the Biofuels and Biochemical Industries, might be the first policy package which explicitly encourage the development of biodiesel [18]. Another policy released later in the same year by MOF reiterated that the construction of both bioethanol and biodiesel plants for non-cereal based biofuel production will be subsidized [19].

According to the Middle and Long Term Development Plan of China’s Renewable Energy [21], annual production of biodiesel is targeted at 0.2 million tons for 2010 and 2 million tons for 2020. To facilitate the development of biodiesel industry, a voluntary biodiesel standard (for 100 percent biodiesel) was announced in July 2007. Standards for B5 and B10 (diesel mixed with 5 or 10 percent of biodiesel) are currently still under discussions. Because there is no mandatory use of biodiesel for automobiles in China, it is not compulsory for biodiesel to comply with those standards at current stage.

In order to achieve the targets of biodiesel production and to avoid the potential conflict with food security, China has been encouraging the production of biodiesel from non-edible tree-based feedstock. Although the 2007 version of the Development Plan of China’s Agricultural Bioenergy Industry (2007–2015) considers rapeseed produced on fallow land as a potential feedstock for biodiesel production, in the later years crop-based biodiesel has been almost completely excluded from the spectrum of government consideration. In 2007, the Development Plan for China’s Bio-forestry Businesses was released by State Forestry Administration (SFA). This plan sets the target for the total area of energy tree plantation by 2020 at 13.3 million hectares, which would be sufficient to provide feedstock for an annual production of 6 million tons of biodiesel [22]. To encourage firms to reclaim new marginal land for energy tree plantation, the MOF committed a one-off subsidy at a level of 3000 yuan per hectare of such new land in the same year [20].

4. Opportunities and challenges for China’s future biofuel expansion

Despite the great efforts China has put into biofuels development, growth in the sector is slow and lags behind both the US and Brazil. It is mainly because China has a large population and faces the constraint of limited and decreasing arable land. While the major established capacity in the sector may continue to use food crops as a feedstock, the future expansion of China’s biofuel production will depend on non-food feedstocks. In the short to medium term a focus on non-cereal bioenergy crops such as cassava and sweet potato and the “one-and-a-half” generation feedstocks such as sweet sorghum would be sufficient for the fulfillment of the planned targets while eventually moving to the second generation (cellulosic) feedstocks.

4.1. Assessment of alternative bioenergy crops and land use

The report “Preparing a National Strategy for Sustainable Energy Crops Development”, produced by a special technical assistant project of Asian Development Bank to the People’s Republic of China in October 2009, might be the first major research work which presents a systematic assessment of the bioenergy crops development in China [23]. While it adopts the estimation of suitable marginal/reserved arable land from Wen and Tang [24] and reaches a similar conclusion to Tian and Zhao [25] in terms of bioethanol production potentials as presented in Table 4,[4] what makes it special is its insight on the potential of sweet sorghum, a

[4] Although the assessment based on terrain, climate and soil quality can put the figure of marginal land available for biomass production at up to 130 million ha [26], it is widely recognized that 24-30 million ha are potentially cultivable and further in consideration of economic operation of transportation, about 7 million ha can be considered available for growing energy crops [27–29].

Table 4
Distribution of suitable marginal land for bioenergy crop by region.

Region	Bioenergy crop	Suitable marginal land (1000 ha)	Bioethanol potential (1000 t) with utilization ratio of		
			10%	20%	50%
Northeast China	Sweet sorghum	453	178	356	890
North China	Sweet sorghum, sweet potato	571	224	448	1120
Loess Plateau	Sweet sorghum, sweet potato	879	344	688	1720
Inner-Mongolia and Xinjiang	Sweet sorghum, sugar beets	3696	1448	2896	7240
Middle and lower Yangtze River	Cassava, sweet sorghum	697	392	784	1960
South China	Sweet potato	124	82	164	410
Southwest China	Cassava	321	180	360	900
Qingzang Plateau	None for environmental protection	0		0	0
Total		7020	2850	5700	14,250

Data source: [23].

promising bioenergy crop which can produce one or two time more ethanol per unit area than maize.

First, because average seed yield of sweet sorghum is almost equivalent to that of sorghum in farmland, to plant sweet sorghum instead of sorghum in previous sorghum planting farmlands would not greatly affect grain production. Thus it is possible to plant sweet sorghum in the current sorghum growing lands. In 2009, the sorghum planting area in China was 550,000 ha, and the total output quantity of seed was about 2.5 million tons [6]. Liaoning, Jilin, Heilongjiang, Inner–Mongolia, Shanxi and Hebei are the major provinces for sorghum planting. If 50% of sorghum growing land can be put into growing sweet sorghum by 2020, the planting areas would produce about 17 million tons of stalks and thus about 1.12 million ton of bioethanol per year. The commercial utilization of sweet sorghum stalks would significantly increase the income of sorghum farmers and contribute to poverty alleviation and rural development.

Second, although the current plantation scale of sweet sorghum is small, mostly in North China, new sweet sorghum varieties with better geographic adaptability, high stalk yield, high brix, and tolerance to saline–alkali stresses have been developed by Chinese scientists, such as Chuntian series, Nengsi series and Liaotian series. In addition to the methods of hybridizing, ion beam radiation, and genetic engineering, spaceflight mutation breeding was conducted recently. By the latter method, the sweet sorghum seeds were placed in a returnable satellite and orbited the Earth for a certain period, finally leading to a mutated sweet sorghum variety possessing improved stem sugar content and a prolonged preservation period as well as decreased size [8].

The key challenge for commercial operation of sweet sorghum ethanol plants is processing technology. Because sweet sorghum in China can be planted only once a year, the standard process of liquid fermentation has led to a very limited operational period of 3–4 months a year at the maximum. In contrast, with the solid state fermentation process the sorghum stalks are simply crushed to produce the raw feedstock for fermentation to produce ethanol. The solid state fermentation process uses ensiling techniques to preserve the sugar and thus decreases the energy cost of sweet sorghum and makes the plants operational for a much longer period in the off-harvest seasons. The current limitation of this technique is that its production period is very long, between three and 14 days, making commercialization economically unattractive. To overcome this limitation, Chinese scientists recently have developed an advanced solid state fermentation (ASSF) process, which reduces the fermentation time to 43 h. The ASSF process takes the same amount of time as the liquid fermentation process and has the potential to further shorten the production cycle. This technique has passed the pilot testing stage and is currently being tested at the commercialization stage [23,30].

The second most promising bioenergy crop might be sweet potato, which has large, starchy, and sweet tasting tuberous roots. Because of its strong ability in drought- and pest-resistance and in tolerance to poor soil fertility, it is extensively cultivated in China. According to FAOstat [31], China produced about 84.4 million tons of sweet potato in 2007 with an average yield of 23.1 tons/ha. Expert opinion indicates that high yields of 45–75 tons/ha can be achieved by promotion of new varieties and improved field management. If the yield doubles in 2020 and the planting area keeps stable at the current level of about 4.5 million hectares per year, an additional 100 million tons of sweet potato can be produced. ADB [23] suggests that there are at least 2 million hectares which have potential for sweet potato plantation. Assuming that the yield in such marginal land will be half of the above assumed 2020 level of 45 tons/ha, an additional 42 million tons of sweet potato can be produced. Further assuming that 50% of the new output will be used for bioethanol production, about 8 million tons of bioethanol can be produced. On the technical side, high starch content varieties such as Chuanshu 34 and Yusu 303 were bred successfully in Sichuan and Chongqing. Breeding new varieties for bioenergy production has been funded by the National "863" and other programs and one of the outcomes, Xushu 22, is planted in Xuzhou Research Centre of Sweet Potato [8,23].

The third promising bioenergy crop would be cassava, a tropical crop which is also characterized by high drought- and pest-resistance, fair tolerance to poor soil fertility, wide adaptability and high starch content. Cassava is cultivated mainly in Guangxi, Guangdong, and Hainan provinces. Data from the Development Office of Sub-tropical Crops in the Ministry of Agriculture of China indicate that in recent years (2006 and onward), the total planting area of cassava has been over 400,000 ha per year with an average yield of 20 tons/ha [28,32]. According to Zhong et al. [8], China has the world-leading process technologies in cassava ethanol production. For example, Guangxi COFCO Bio-energy Co. Ltd presented in Table 1 is currently the largest, single manufacturing unit to produce fuel ethanol from cassava in the world. The unit utilizes state of the art techniques such as gelatinization via low temperature cooking, continuous high-gravity fermentation, high-efficiency precise rectification, whole process simulation, pressure swing adsorption (PSA) and temperature swing adsorption (TSA). This package of techniques was developed by Chinese scientists and engineers in Tianjin University. As in the case of sweet potato, the key constraint/challenge to the cassava-based bioethanol production is the breeding and spreading of new varieties and improvement in field management. As indicated in ADB [23], if a higher yield of 45 tons/ha can be reached in 2020 by spreading the existing new varieties such as Huanan 5, Huanan 8, and Nanzhi 199, an additional 2.2 million tons of cassava ethanol can be produced every year without an extension of the current planting areas.

Moreover, in the earlier period of growth before the shoots and leaves meet, intercropping of watermelon and spring soya can improve the productivity of the land and increase the income of farmers.

The above accounting indicates that the potential of alternative bioenergy crops is strong in China. If existing high yield varieties of sweet sorghum, sweet potato, and cassava can be popularly adopted and properly managed, the annual production target of 10 million tons bioethanol can be met without extending the current planting areas to marginal land or competing with food production. This insightful inspection has been largely overlooked in the existing literature. With this observation in mind, bioethanol potentials from marginal land as presented in Table 4 would further enhance the potential of alternative bioenergy crops. Such strong potential implies that alternative bioenergy crops can play an important role in China's efforts to address its energy security concern before the arrival of commercially viable cellulosic biofuels.

4.2. Assessment of conversion technologies

In the standard bioethanol production process of cooking, liquefaction and saccharification, the temperature of the cooking process is higher than 100 °C, which results in significant energy consumption. The recent innovative advancement in the first-generation technology is led by development in low temperature cooking process. The new process synchronizing the saccharification and fermentation process and reduces the cooking temperature to 50 °C. Consequently, it eliminates the separate equipment for saccharification, decreases the probability of bacterial contamination, and reduces the restrainability of high sugar concentration to microzyme [23]. If this new process can be adopted in China to replace the standard process, significant yield improvement and cost reduction in bioethanol production from starchy feedstock can be achieved.

In terms of the "one-and-a-half" generation technology, the availability of the advanced solid state fermentation (ASSF) technology as we discussed in the Section 2.1 and Section 4.1, in combination with other technologies in seed breeding, preservation of sweet sorghum juice, etc., has laid a solid foundation for industrial-scale bioethanol production from sweet sorghum. The challenge ahead lies on (a) providing incentives as well as information and technological supports for new and existing farmers to grow sweet sorghum in their crop mix and/or in marginal and abandon land, and (b) locating production plants and feedstock sources strategically to maximize logistical and transportation efficiency.

Although second-generation biofuels are not yet produced commercially, significant technological progress has been made and a great number of pilot and demonstration plants have been set up in recent years across the world. Many believe that China has the potential to become a leader in cellulosic technology. For example, in addition to the continuous steam explosion process jointly developed by COFCO and Novozymes as already mentioned in the Section 2.1, Tianguan Group, a major Chinese ethanol producer, has developed a feedstock pre-treatment line, increased the conversion rate from sugar to ethanol, and bred effective strains. Longli Group, in partnership with Chinese universities to develop commercializing technologies of maize cob processing, has achieved high cell conversion rates (as high as 80 percent), and has found a pre-treatment process that avoids the pentose problem [33].

A cutting edge development is the SMEHF (simultaneous multi-enzyme synthesis and hydrolysis separate fermentation) process developed by Tsinghua University in collaboration with Oxford University. This technology includes (a) pre-treating lignocelluloses by a bio-chemical method of combining dilute acidic hydrolysis assisted by molecule vibration with a consortium of microorganism to decompose lignin partially, thus exposing more cellulose surface to benefit the adsorption of cellulases; (b) hydrolyzing cellulose by a consortium of fungi which can produce more cellulases to breakdown cellulose into glucose, with the idea that different cellulases can synergically decompose cellulose originating from the traditional Chinese medicine; (c) and improving ethanol producer through genetic modification to modify the abilities of Zymomonas mobilis. It is expected that this SMEHF technology can become commercially operational by 2015 [30].

As Ha et al. [34] highlight, the use of plant biomass for commercially vital biofuel production requires efficient utilization of the sugars in lignocelluloses, primarily glucose (a six-carbon sugar, relatively easy to ferment) and xylose (a five-carbon sugar, much more difficult to utilize in ethanol production). However, strains of Saccharomyces cerevisiae presently used in bioethanol production ferment glucose but not xylose. Yeasts engineered to ferment xylose do so slowly, and cannot utilize xylose until glucose is completely consumed. Fortunately, this critical bottleneck has been recently overcome by a group of scientists at the University of Illinois, the University of California, the Lawrence Berkeley National Laboratory, Seoul National University and the energy company BP. They engineered yeast strains that can ferment cellobiose and xylose simultaneously and thus successfully integrate cellobiose and xylose fermentation pathways in yeast. The new strains, made by combining, optimizing and adding to earlier advances, reduce or eliminate several major inefficiencies associated with current biofuel production methods. This success is a critical step towards enabling economic biofuel production [34].

Despite these significant technological progresses within and outside China, many challenges remain. The chief challenge is that the huge biomass demand (up to 600,000 tons/year) for a commercial second-generation biofuel plant requires a complex logistics system and good infrastructure to provide biomass at economically competitive costs [35]. However, it is also worth noting that while the costs of second-generation biofuel production are speedily declining due to technology progresses, increasing conversion efficiency and improvement in transport logistics, the reference crude oil price has increased more than 250 percent from the bottom of the financial crisis in Dec 2008 [36] and is well on the way to approach USD120/barrel in 2011–2012. Interestingly, the assessment of IEA [35] based on IEA Mobility Model database suggests that if the oil price reaches USD120/barrel, biofuel production based on currently available second-generation technologies in China would be able to break even ([35], p. 129). It implies that if oil price reaches USD140/barrel as was witnessed in July 2008, the second-generation biofuel production with current technology would become commercially profitable and attractive. The combination of a rising oil price and significant technological breakthroughs such as the integration of cellobiose and xylose fermentation pathways in yeast would make second-generation biofuel production commercially viable within the next decade.

4.3. Potential environmental and social impacts

To combat global warming is one of the underpinnings for the biofuel rush in both China and other countries. The intuition is that the combustion of biofuels is carbon neutral, meaning that there is no net carbon release to the air, because feedstock for biofuel production takes carbon dioxide out of the air. However, when considering the greenhouse gas (GHG) emission of biofuel from a full life cycle perspective, the carbon neutrality proposition may no longer hold, particularly in relation to the first-generation technology. For example, the production and transportation of feedstocks, and the conversion process of feedstock to biofuels all need fuel energy inputs, such as fertilizer, pesticide, machinery, and steam. Some studies have showed that from a lifecycle perspective,

the reduction of GHG emission by using biofuel is insignificant, and other negative environmental consequences may offset the intended future climate benefits [37,38].

While these findings suggest weak contributions of first-generation biofuel to the reduction of GHG emission, the widespread opposition to the promotion of the first-generation biofuel results from its threat to food security. In a global context, the in-depth assessment of Fischer et al. [39] strongly indicates that first-generation biofuels compete with food supply and are not tenable in the long-run. Brown [40] argues that “the competition for grain between the world’s 800 million motorists who want to maintain their mobility and its 2 billion poorest people who are simply trying to survive is emerging as an epic issue”, and “soaring food prices could lead to urban food riots in scores of lower-income countries that rely on grain imports, and the resulting political instability could in turn disrupt global economic progress, directly affecting all countries”. An IFPRI report [41] shows that if the world’s major biofuel producing countries (especially US, Brazil, EU, and China) expand their biofuel production according to their stated plans for 2020 and using the current first-generation technologies, this would lead to significant increases in world prices for the various feedstock crops used. The price of maize, oilseeds, sugarcane and wheat would rise by about 41%, 76%, 66% and 30%, respectively, in comparison with the baseline where such an expansion is absent.

Assessments of the first-generation biofuel development in the context of China raise the same food security concern given the persistent tight balance in supply and demand of grain in the country. For example, Yang et al. [42] estimate that to produce 10 million tons of bioethanol in 2020, about 5–10% of China’s farmland would be occupied for feedstock production. Qiu et al. [43] employ a general equilibrium model for China and show that if no new marginal land was to be cultivated for feedstock production, China would need to import about 30 percent of total feedstock consumption from the world market to meet its bioethanol target of 2020. As we have discussed in previous sections, the great concerns on food security within China has led to China’s biofuel policy shifting away from cereal-based to alternative biofuel development.

In contrast to the first-generation biofuels, the profiles of the second-generation as well as the “one-and-a-half” generation biofuels are much more positive in terms of environmental and social impacts. China produces about 600 million tons of crop straw and stalks and 900 million tons of woody residuals every year in recent years. Roughly 40–50% of crop straw and stalks and 20–30% of woody residual and wastes can be collected with low costs for biofuel production [16]. Such a utilization of by-products from cereal and forest commodities production will not only boost the income of farmers but also have a high GHG mitigation potential of more than 60% according to IEA [35] and thus reduce lifecycle CO_2 emissions by replacing fossil fuels. The planting of energy crops like switchgrass in marginal land could increase vegetation coverage, sequester carbon, reduce soil erosion, and improve the environment in the local areas and beyond. Such land otherwise is covered by small weed plants that contribute little in terms of mitigating soil erosion and GHG emission [27,35].

The Chinese rural economy is in general underdeveloped and has been a problem of national significance. Development of a biofuel industry centered on “one-and-a half” and second-generation technologies will provide significant new opportunities for economic development in rural areas. Growing crops and trees will become a multiple purpose business and consequently the rural economy will be improved in multiple ways. Selling of straws and stalks at an attractive price will directly increase farmers’ income. Straw collection, storage and transport will offer additional jobs. Energy crop cultivation and downstream processing of cellulosic ethanol is a new industrial chain which will mainly be located in rural areas and thus generate employment opportunities for the rural labor force.[5] Increased fodder production as a by-product of biofuel production will also increase livestock rearing [27,35,44]. On the other hand, the spreading of biofuel plants over the rural areas would bring in the challenges of controlling pollution from the production process as China has experienced in the development process of township and village industrial enterprises [45]. Particular attention must be paid to water pollution. It is very important for modern biofuel plants to be integrated with sufficiently sophisticated water treatment techniques so as to enable the recycling of water back to the boilers and to control water pollution [23,35].

5. Concluding remarks

Liquid biofuels such as bioethanol and biodiesel are attractive substitutes for petroleum-based fuels because biofuels are renewable, can be produced from domestic resources with an environmentally friendly emission profile, and are readily biodegradable. China has taken steps to participate in the biofuel revolution since the early 2000s. The major impetus for investment in the biofuel sector has been the nation’s great concerns on energy security. It is also seen as a way to support farm incomes. After years of discussions, debates, and pilot production, an annual production target of 10 million tons of bioethanol and 2 million tons of biodiesel in 2020 has been set. Although the target is less ambitious than some campaigners in China originally advocated, it strikes a proper balance between the two security issues of food and energy. To safeguard food security, the current regulations unambiguously require that all future biofuel expansion in China must be non-cereal based and must not compete with cereal production over land.

Based on in-depth interviews with experts in the field and on a thorough review of existing studies, in this paper we further examine potential opportunities and challenges for the future expansion of China’s liquid biofuel industry. We find that the potential of alternative bioenergy crops such as sweet sorghum, sweet potato, and cassava are strong and can play an important role in China’s efforts to address its energy security concern before the arrival of commercially viable cellulosic biofuels. In more detail, if the existing high yield varieties can be widely adopted and properly managed in the currently growing areas of those crops (with feasible substitution of sweet sorghum for sorghum growing), the annual target of 10 million tons bioethanol can be met without competing with food production. The potentials of alternative bioenergy crops can be further significantly enhanced if those high yield varieties to be also cultivated in economically accessible marginal land.

We also find that China is in a leading position in terms of “one-and-a-half” generation technology such as the advanced solid state fermentation (ASSF) of crushed sweet sorghum stalks and second-generation technology such as the simultaneous multi-enzyme synthesis and hydrolysis separate fermentation (SMEHF) of crop straw and stalks. Although the huge biomass demand for a commercial “one-and-a-half” or second generation biofuel plant would lead to high transportation and logistics costs, once the price of crude oil exceeds USD120 per barrel, China’s existing “one-and-a-half” and second generation biofuel plants would be able to reap profit. The combination of foreseeable rising in oil prices and recent significant technological breakthroughs such as the integration of cellobiose and xylose fermentation pathways in yeast suggests that the second-generation biofuel production would become commercially viable within the next decade. China is on the right track to

[5] IEA [35] indicates that an enterprise with an annual production capacity of 10,000 t of cellulosic ethanol typically provides jobs for about 200 people.

make a smooth transition from the first-generation to the second-generation biofuel production.

Despite these bright and encouraging prospects, many challenges remain. In this concluding section, we would like to highlight the following three: (a) providing incentives as well as information and technological support for new and existing farmers to grow sweet sorghum in their crop mix and to grow other energy crops and trees in marginal and abandoned land; (b) developing transport infrastructure and locating production plants and feedstock sources strategically to maximize logistical and transportation efficiency; and (c) integrating sufficiently sophisticated water treatment techniques into modern biofuel production plants so that the plants are capable of effectively recycling water back to the boilers and controlling water pollution.

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References

[1] Li W. Record reliance on foreign oil in Q1. Global Times, May 26, 2010. Document available online: http://business.globaltimes.cn/china-economy/2010-05/535329.html.

[2] IEA. World energy outlook 2008. Paris: International Energy Agency; 2008.

[3] Parker L, Blodgett J. Greenhouse gas emissions: Perspectives on the top 20 emitters and developed versus developing nations. Congressional Research Service (CRS) Report for Congress, RL32721. Washington DC; 2010.

[4] Mastny L. 2010. Renewable energy and energy efficiency in China: current status and prospects for 2020, Washington DC, Worldwatch Report, Worldwatch Institute.

[5] Carriquiry M, Dong F, Du X, Elobeid A, Fabiosa JF, Chavez E, Pan S. World market impacts of high biofuel use in the European Union. Working Paper 10-WP 508, Center for Agricultural and Rural Development, Iowa State University; 2010.

[6] NBSC (National Bureau of Statistics of China). China statistical yearbook. Beijing: China Statistics Press; 2010.

[7] EIA. (Energy Information Administration), International Energy Statistics, 2009. Available online at: www.eia.doe.gov/emeu/international/contents.html.

[8] Zhong C, Cao Y, Li B, Yuan Y. Biofuels in China: past, present and future. Biofuels, Bioproducts & Biorefining 2010:326–42.

[9] The company's website: http://www.lianhai.cn/en/about.asp.

[10] O'Kray C, Wu K. Biofuels in China: Development dynamics, policy imperatives, and future growth. IAEE Energy Forum, 2nd Quarter 2010: 21–24. Document available online: http://www.iaee.org/cn/publications/fullnewsletter.aspx?id=14.

[11] GACC (General Administration of Customs of China). China monthly export & imports. Beijing: General Administration of Customs of China; 2011. January Issue of 2011 (in Chinese).

[12] BioZio. Sample content of the comprehensive jatropha report. BioZio, Tamilnadu, India; 2010. Document available online: http://www.biozio.com/ref/report/jat/Comprehensive_Jatropha_Report_Preview.pdf.

[13] GSI. (Global Subsidies Initiative). Biofuels–At What Cost? Government support for ethanol and biodiesel in China. A report Prepared by the Global Subsidies Initiative (GSI) of the International Institute for Sustainable Development (IISD), Geneva, Switzerland; 2008.

[14] Chew C. 2006. Current status of new and renewable energies in China: introduction of fuel ethanol, Report to the Institute of Energy Economics, Japan.

[15] ADB. (Asian Development Bank). Status and potential for the development of biofuels and rural renewable energy: The People's Republic of China. ADB, Manila, Philippines; 2009. Document available online: http://www.adb.org/Documents/Reports/Biofuels/biofuels-prc.pdf.

[16] Wang Q. Time for commercializing non-food biofuel in China. Renewable and Sustainable Energy Reviews 2011;15:621–9.

[17] NDRC (National Development Reform Committee). Strengthen the management of new bioethanol projects and promoting the sustainable development of biofuel industry. Beijing: NDRC; 2006.

[18] MoF (Ministry of Finance). Policy provision on financial support to biofuel and biochemical industries. Beijing: MoF; 2006.

[19] MoF (Ministry of Finance). Guidance on the implementation of financial support to non-cereal based biofuel development. Beijing: MoF; 2006.

[20] MoF (Ministry of Finance). Temporary policy provision on financial subsidies to production bases of feedstocks for biofuel and biochemical industry. Beijing: MoF; 2007.

[21] NDRC (National Development Reform Committee). Medium- and long-term development plan for China's renewable energy. Beijing: NDRC; 2007.

[22] SFA (State Forestry Administration). Planning for China's bio-forestry development: 2020. Beijing: SFA; 2007.

[23] ADB. (Asian Development Bank). Preparing a national strategy for sustainable energy crops development. ADB TA-4987 (PRC) Component B, Final Report; 2009. Document available online: http://www.adb.org/Documents/Reports/Consultant/PRC/41589/41589-01-prc-tacr.pdf.

[24] Wen M, Tang C. Reserve of arable land resources in (the) PRC. Beijing: China Land Press; 2005 (in Chinese).

[25] Tian Y, Zhao L. Preliminary analysis on sustainable supply of raw materials for fuel ethanol in (the) PRC, Energy China; 2007: issue 12 (in Chinese).

[26] Zhuang D, Jiang D, Liu L, Huang Y. Assessment of bioenergy potential on marginal land in China. Renewable and Sustainable Energy Reviews 2011;15:1050–6.

[27] Tang Y, Xie J, Geng S. Marginal land-based biomass energy production in China. Journal of Integrative Plant Biology 2010;52(1):112–21.

[28] Tian Y, Zhao L, Meng H, Sun L, Yan J. Estimation of unused potential for biofuels development in (the) People's Republic of China. Applied Energy 2009;86(S1):77–85.

[29] Yan L, Zhang L, Wang S, Hu L. Potential yield of bioethanol from energy crops and their regional distribution in China. Transaction of the CSAE 2008;24: 213–6.

[30] Li S, Chan H. Ethanol production in (the) People's Republic of China: potential and technologies. Applied Energy 2009;86(Suppl 1):S162–9.

[31] FAOstat. 2009. Data available online: http://faostat.fao.org.

[32] Qiu H, Huang J, Yang J, Rozelle S, Zhang YuH, Zhang YaH, et al. Bioethanol development in China and the potential impacts on its agricultural economy. Applied Energy 2010;87:76–83.

[33] USDA. Readout from Sino-U.S. advanced biofuels forum. USDA Foreign Agricultural Service GAIN Report Number: CH10035, July 30, 2010, Washington DC; 2010.

[34] Ha SJ, Galazka JM, Kim SR, Choi JH, Yang X, Seo JH, et al. Engineered Saccharomyces cerevisiae capable of simultaneous cellobiose and xylose fermentation. Proceedings of the National Academy of Sciences 2011;108(2):504–9.

[35] IEA. Sustainable production of second-generation biofuels: potential and perspectives in major economies and developing countries. Paris: International Energy Agency; 2010.

[36] IMF. (International Monetary Fund). IMF primary commodity prices. The version of February 10, 2011.

[37] Scharlemann JPW, Laurence WF. How green are biofuels. Science 2008;319:43–4.

[38] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science Express 2008;319:1238–40.

[39] Fischer G, Hizsnyik E, Prieler S, Shah M, van Velthuizen H. Biofuels and food security. Research Report, International Institute for Applied Systems Analysis (IIASA); 2009.

[40] Brown LR. Distillery demand for grain to fuel cars vastly understated: world may be facing highest grain prices in history. Report of Earth Policy Institute, Washington, DC; 2007.

[41] von Braun J, Pachauri RK. The promises and challenges of biofuels for the poor in developing countries. IFPRI Essay, International Food Policy Research Institute, Washington DC; 2006. Document available online: www.ifpri.org/sites/default/files/publications/ar05e.pdf.

[42] Yang J, Huang J, Qiu H, Rozelle S, Sombilla MA. Biofuels, the Greater Mekong subregion: assessing the impact on prices, production and trade. Applied Energy 2009;86:S37–46.

[43] Qiu H, Huang J, Keyzer M, van Veen W, Rozelle S, Fischer G, et al. Biofuel development, food security and the use of marginal land in China. Journal of Environmental Quality 2011;40(4):1058–67.

[44] Lu L, Tang Y, Xie J, Yuan Y. The role of marginal agricultural land based mulberry planting in biomass energy production. Renewable Energy 2009;34(7):1789–94.

[45] Wang M, Webber M, Finlayson B, Barnett J. Rural industries and water pollution in China. Journal of Environmental Management 2008;86: 648–59.